# A METHOD OF IMPROVING THE EFFICIENCY OF KLYSTRONS

By

**Richard H. Winkler**

**Technical Report**

Prepared under Office of Naval Research Contract
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**M.L. Report No. 235**
**May, 1954**

*Microwave Laboratory*
W. W. Hansen Laboratories of Physics
Stanford University
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LIST OF FIGURES

TABLE OF CONTENTS

## NOMENCLATURE

| | |
|---|---|
| $a = \frac{du}{dt}$ | electron acceleration |
| $d$ | distance between entrance and exit plane |
| $t$ | time |
| $t_1$ | time at crossing entrance plane |
| $u = \frac{dz}{dt}$ | electron velocity |
| $u_0$ | input velocity of electron at entrance plane |
| $z$ | distance from entrance plane |
| $D = \frac{\omega d}{u_0}$ | normalized distance between entrance and exit plane |
| $V$ | peak r-f gap voltage between entrance and exit plane |
| $V_0 = \frac{u_0^2}{2e/m}$ | potential corresponding to input velocity $u_0$ |
| $Y$ | normalized distance |
| $Z = \frac{\omega z}{u_0}$ | normalized distance from entrance plane |
| $\alpha = \frac{V}{V_0}$ | normalized gap voltage |
| $\omega$ | frequency |

## ACKNOWLEDGMENT

The author wishes to acknowledge the help of Professor E. L. Ginzton, Director of the Microwave Laboratory, whose faith and enthusiasm contributed greatly toward the completion of the project; and the author wishes to thank the many members of the Laboratory staff who have helped with the construction of the apparatus described in the present report.

# I. INTRODUCTION

A klystron is essentially a device for converting one form of electric power into another form. In particular, one is usually converting d-c or pulsed d-c power to a-c power whose frequency is in the thousands of megacycles per second.

The klystron is composed of three physically distinct structures: first, an electron gun which converts the d-c power represented by electrons flowing in a pair of wires, with a potential between the wires, to an electron beam in which the power is represented by the kinetic energy of the electrons; second, an r-f structure which extracts some fraction of the kinetic energy in the form of radio-frequency electric power; and third, a collector for dissipating the remaining kinetic energy of the beam.

The best r-f structures available rarely are capable of converting more than 40 per cent of the beam power to r-f power. The remainder is generally dissipated as heat.

It is possible to reconvert some of this remaining kinetic beam power into electric power again in a manner suitable for use at the electron gun. This is accomplished by slowing electrons down with a retarding d-c electric field produced by a segmented collector, the several segments being at a negative potential with respect to the drift tube. Sufficient power can be reused so as to reduce significantly the net power input.

This report is devoted to the problem of designing, building, and testing a collector which will reconvert some of the beam power and increase the net tube efficiency (defined by the ratio of the r-f power output to the net d-c power input).

A collector for a 2-Mw pulsed klystron amplifier was built and tested. The beam had a perveance of $2 \times 10^{-6}$ amp/$v^{3/2}$ and 10 kw of maximum average power. The special collector resulted in a recovery of 24 per cent of the beam kinetic energy. The r-f efficiency of the tube without the special collector was 21 per cent. The special collector thus provided an improvement in over-all efficiency to $21/(100 - 24) = 28$ per cent.

On the basis of the measurements taken, it is estimated that an easily constructed collector should recover 30 per cent of the beam power. A properly designed klystron should have an initial r-f efficiency of 30 to 40 per cent. The addition of such a collector would increase the net efficiency to 43 to 57 per cent.

The addition of such a collector would thus result in a reduction in power-supply requirements corresponding to delivering 30 per cent less current than would otherwise be required. This is an obvious saving in power-supply components and in the cost of electric power over the life of the tube. These savings must be balanced against the added cost of the collector and the more complicated operation. In high-power tubes, the addition of such a device would appear to be indicated.

## II. STUDY OF R-F STRUCTURE

To design a collector one should study the characteristics of the beam entering the collector, i.e., the beam leaving the output gap.

Very complicated things happen to the electrons prior to their arrival at the output gap. They interact with focusing electrode fields, image charges, gap fields, magnetic fields, gas ions, etc. But nothing disrupts the beam so violently as do the output-gap fields.

For maximum output gap efficiency, the gap voltage is about equal to the d-c beam voltage. In a gap-coupled klystron (as opposed to a grid-coupled klystron) the electric field at the gap has a significant radial component. These fields are a function of both radial and longitudinal position.

The interaction between gap fields and electrons has been studied by Zitelli.[1] In the small-signal theory, the electrons which are not accelerated in a longitudinal direction are accelerated radially, and vice versa. The magnitude of these accelerations is (in the case of a d-c beam entering the gap) such as to keep the current density constant. A bunch, then, is not so much a crowding together of electrons

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[1] L. T. Zitelli, "Space charge effects in gridless klystrons," Microwave Laboratory Report No. 149, Contract N6onr 25123, Stanford University, October, 1951.

but rather an increase in the current because of a larger beam. The maximum slope of the beam edge is $\frac{1}{4}\alpha k'a$. It can be seen from Fig. 2.2 that the largest pulses of current leaving the output gap are displaced by about $90^{\circ}$ on either side of the bunch center, at just the time the largest radial accelerations exist.

For typical tubes $k'a$ and $\alpha$ are about unity, so that the maximum slope of the beam edge is approximately $\pm 0.25$.

It is possible to make a graphical construction from which electrons can be simply traced through a gridded gap. If one were to follow a single electron through a gap and plot the distance traveled against time, he would find the path curved. However, by a suitable transformation of variables the electron path can be made a straight line and the boundaries, the input and output grid, be curved. This technique is described by Garbuny[1] and is developed in the Appendix.

If space-charge forces are neglected and it is assumed that the klystron gaps are formed by parallel planes, it is possible to trace a number of electrons, say 30, through a klystron and find their exit times and velocities. The efficiency of such a klystron can be calculated from a summation of their exit energies.

One can extend the technique to a gap-coupled tube by assuming that the existing field can be replaced by a constant field of finite length.

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[1] M. Garbuny, "Graphical representation of particle trajectories in a moving reference system," J. Appl. Phys., 21: 1054 (1950).

It is interesting to see what the minimum electron exit velocity is for different gap spacings and $\alpha = 1$. This value of $\alpha$ is very close to that necessary for maximum efficiency for all gap spacings. The minimum value of gap transit angle is generally in the vicinity of 1 radian. In gap-coupled tubes, the equivalent gap along the axis of the beam may be 3 radians. Minimum electron velocities found by tracing electrons are shown in Fig. 2.1. The output-gap efficiencies shown are perhaps incidental to this discussion. They are derived from Fig. 12, Chapter I, of Feenberg's report.[1]

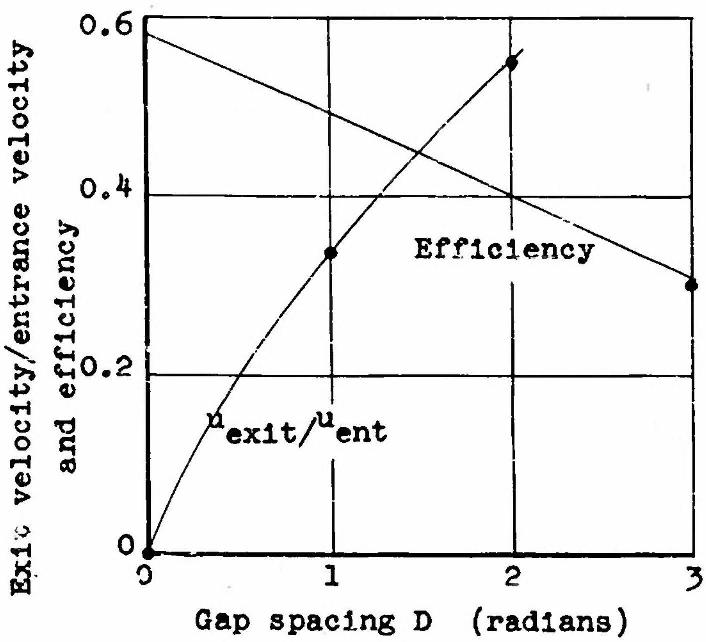


**FIG. 2.1--Exit velocity and output-gap efficiency vs gap spacing for a gridded klystron.**

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[1] E. Feenberg, "Notes on velocity modulation," Sperry Gyroscope Co. Report No. 5321-1043, September, 1945.

One might expect that for maximum efficiency the minimum exit velocity would be zero. Fig. 2.1 indicates that the minimum velocity is by no means small. In a gap-coupled klystron with 1 radian between gap faces, the minimum velocity into the collector is one third of the beam velocity.

The results of trajectory studies on thirty electrons in a gridded-gap klystron whose output-gap transit angle was $2\pi/3 = 2.1$ radians are shown in Table 1 and Fig. 2.2. These computations do not include space-charge or radial acceleration effects. The average current is measured by the number of electrons per unit time crossing the exit plane. For example, during the one-half cycle centered on the antibunch, 5 electrons cross the exit plane where in the d-c case, 15 would cross. The average current is therefore $5/15 = 0.333$ times the d-c current.

The r-f power output is calculated by a summation of the energy of the thirty individual electrons and comparing it with the d-c energy.

Table 1.--Electron beam leaving output gap.

| | Average current per half cycle | Estimated average voltage | $\frac{\text{(Beam perveance per half cycle)}}{\text{(d-c perveance)}}$ | Percentage of d-c beam power |
|---|---|---|---|---|
| $\frac{1}{2}$ cycle centered on bunch | $1.67\ I_0$ | $0.49\ V_0$ | 4.87 | 0.41 |
| $\frac{1}{2}$ cycle centered on antibunch | $0.33\ I_0$ | $1.44\ V_0$ | 0.193 | 0.24 |
| | | | R-f power output | 0.33 |
| | | | Total | 0.98 |

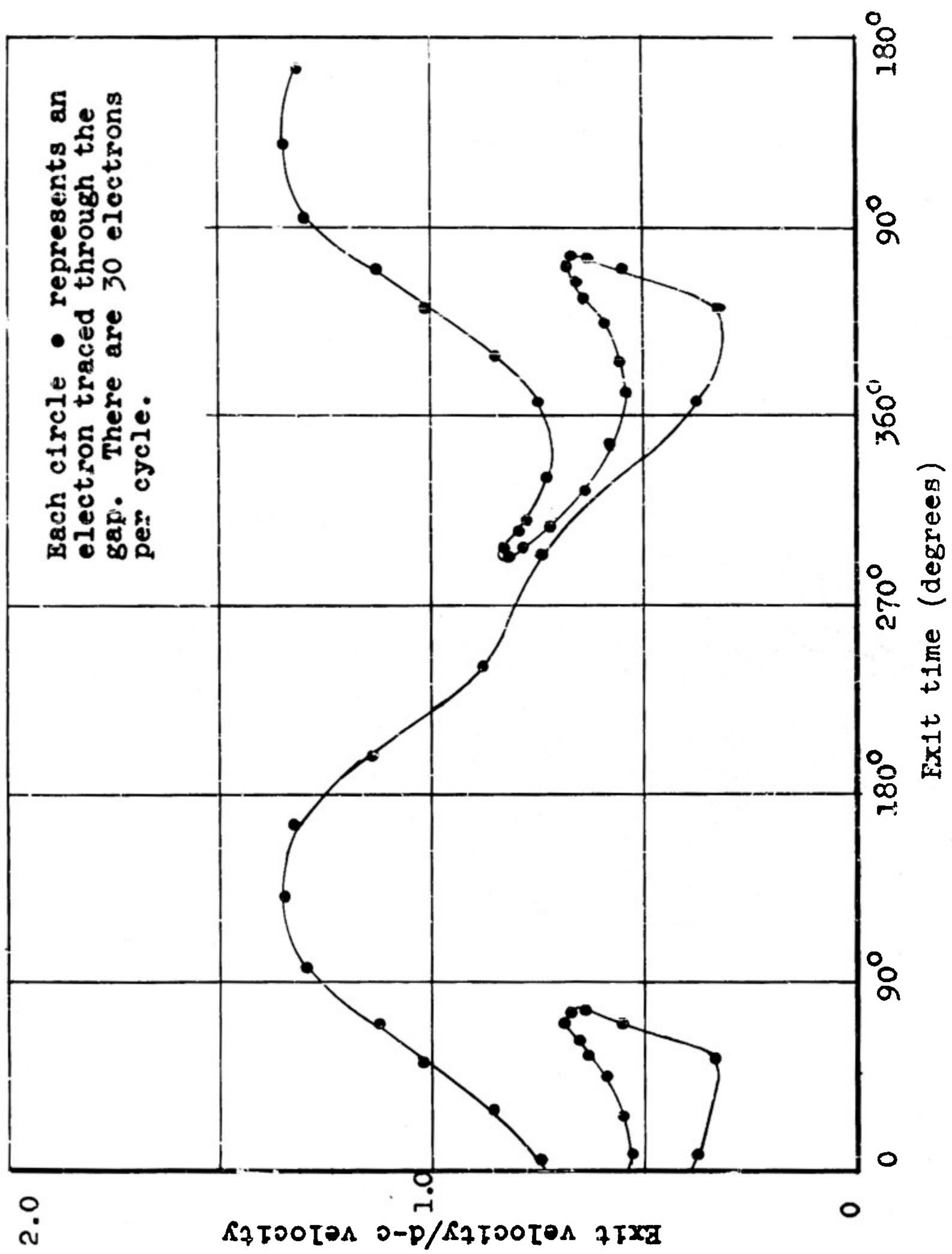


FIG. 2.2--Output gap exit velocity vs time.

The beam perveance averaged over one half-cycle centered on the bunch is many times larger than the d-c perveance. Likewise, the beam perveance averaged over the one half-cycle centered at the antibunch is many times smaller. It is significant to determine over what distance the beam maintains the character represented by the half-cycle data, that is, before the electrons become mixed. If two electrons of potential 0.49 $V_0$ and 1.44 $V_0$, respectively, leave the output gap one half-cycle apart, and the d-c potential $V_0$ is 80 kv, they will pass each other 1.7 in. from the gap. Assuming the initial beam diameter is 0.500 in., the one half-cycle of electrons centered on the bunch considered as a d-c beam will almost quadruple its diameter in that 1.7 in., whereas the antibunch half-cycle will remain essentially unchanged (see Fig. 2.3).

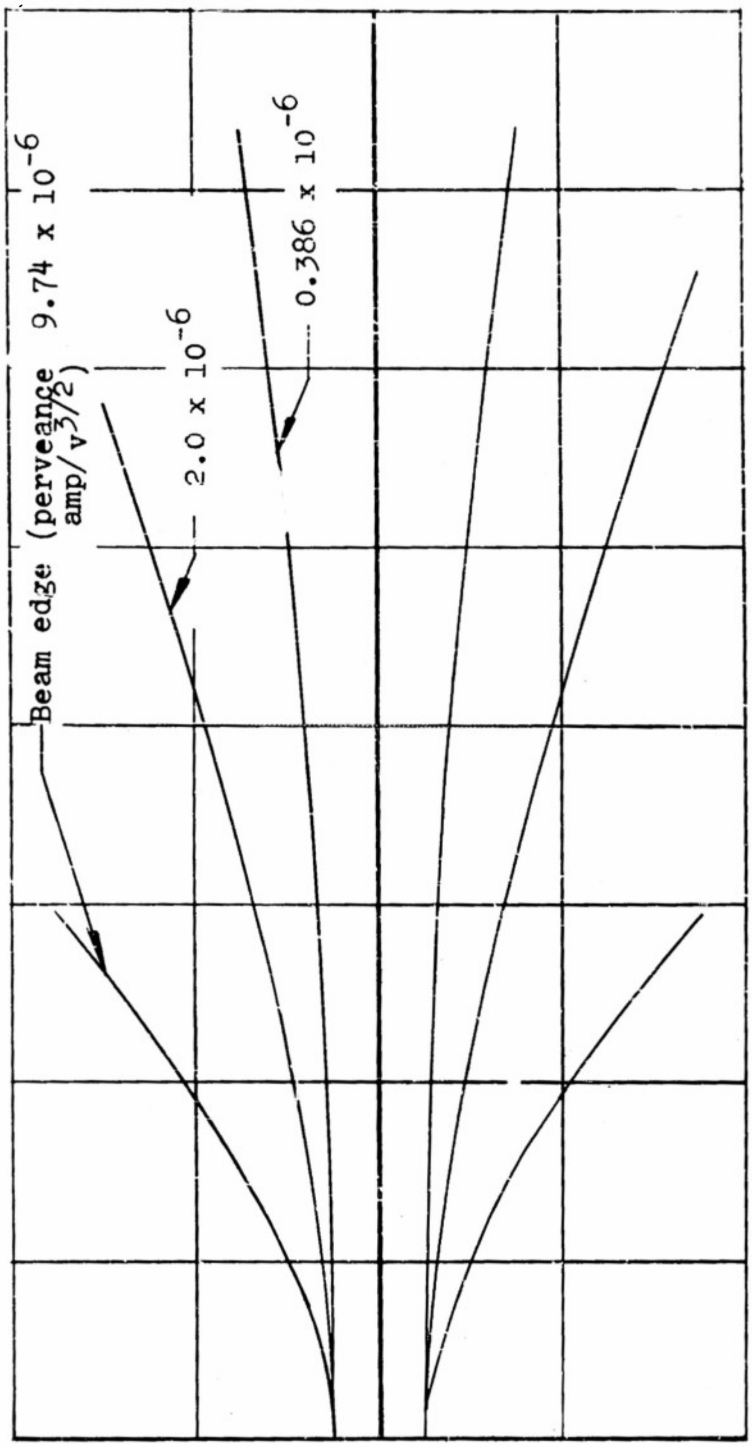


FIG. 2.3--D-c beam-spreading curves.

## III. GENERAL DISCUSSION OF COLLECTING DEVICES

The object of the collector is to retrieve as much power as possible from the beam without disturbing the conditions in the r-f section of the tube.

To convert the kinetic energy of the electron to electric energy one must slow down the electrons with an electric field. To bring an electron of velocity u to a standstill, it must be acted upon by an electric field E, such that when the electron has traversed the distance $\ell$, the following relationship applies:

$$\frac{mu^2}{2} = e\int_0^{\ell} E \cdot ds$$

If the electron alights on an electrode just as it is stopped, this implies the potential difference V between the point at which the electron enters the field E and the point at which it alights is

$$V = -\int_0^{\ell} E \cdot ds$$

so that

$$\frac{mu^2}{2} = -eV$$

If the potential difference between the beam and the drift tube is neglected, the potential difference V is equal to that between the drift tube structure and the collector electrode.

This implies that in order to bring all the electrons to a standstill, one needs electrodes at potentials corresponding to every different electron velocity. Actually, one is limited to a few electrodes. Their potentials must be selected so as to optimize the electric power collected.

If we have a number of electrodes at voltages $V_1, V_2, V_3, \ldots$ in order of decreasing potential, all the electrons going faster than $u_1 = \sqrt{2eV_1/m}$ should go to the first electrode. All those electrons whose velocities lie in the range $u_1 = \sqrt{2eV_1/m}$ to $u_2 = \sqrt{2eV_2/m}$ should go to the second electrode, etc.

It is obvious that the collector should have not only a means of slowing down the electrons, but also of directing them to the proper electrode.

If one knows the distribution of current in small increments of velocity, vs velocity, then one can calculate how much power it is possible to collect with any electrode or set of electrodes. From the data of Fig. 2.2, it is easy to derive a curve, Fig. 3.1, of captured collector power vs collector voltage for the hypothetical klystron discussed on page 6.

A large number of distributions were studied to determine the sensitivity of the power collected to the shape of the distribution curve. Typical values are 25 to 40 per cent of the beam power recaptured for a one-electrode collector, 35 to 50 per cent for two, and 45 to 65 per cent for three. The triangular distribution shown in Fig. 3.2 closely approaches the results for the hypothetical klystron. A single collector can recapture 28 per cent of the beam power and a

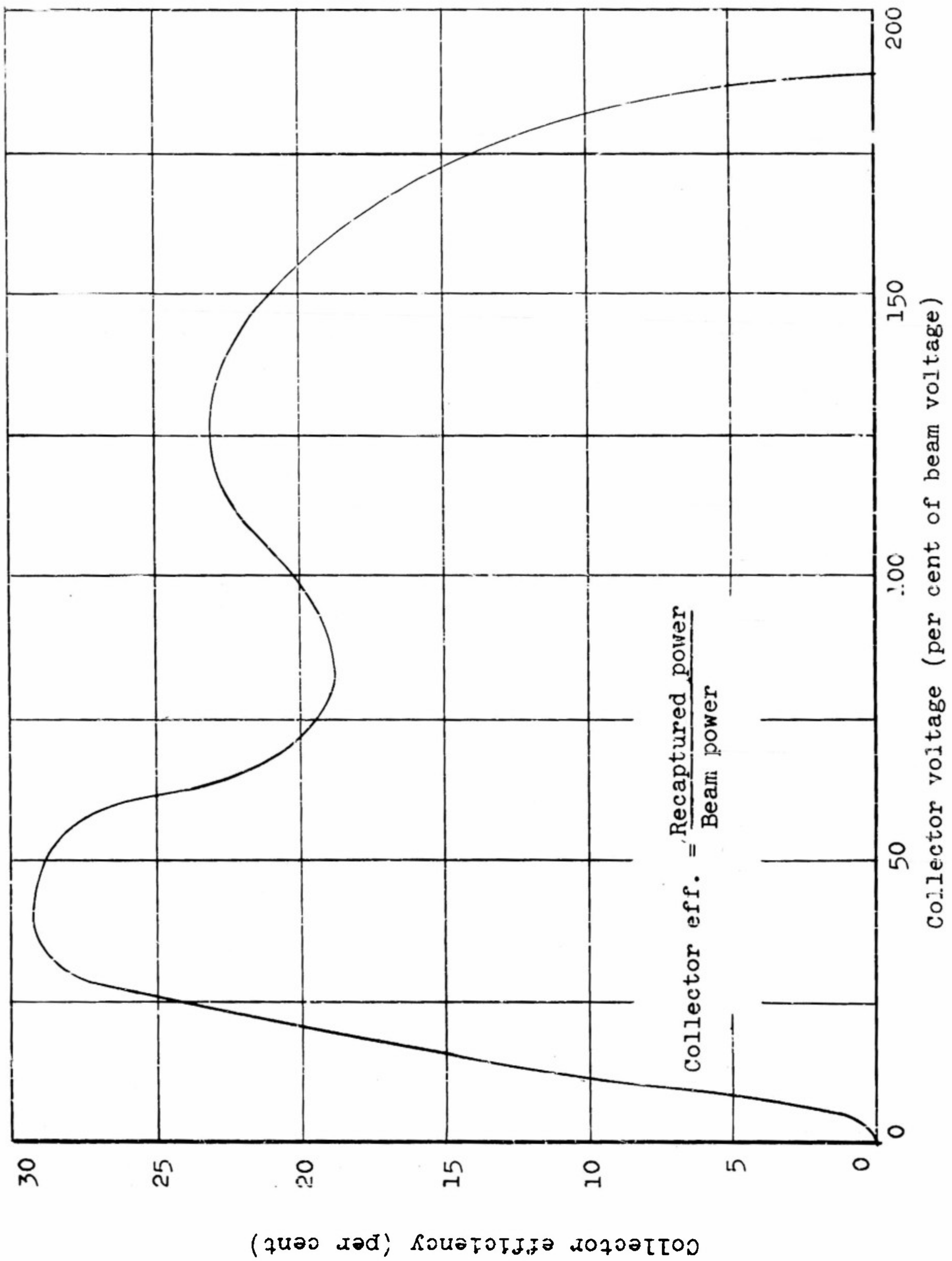


FIG. 3.1--Recaptured power vs collector voltage for a single electrode collector.

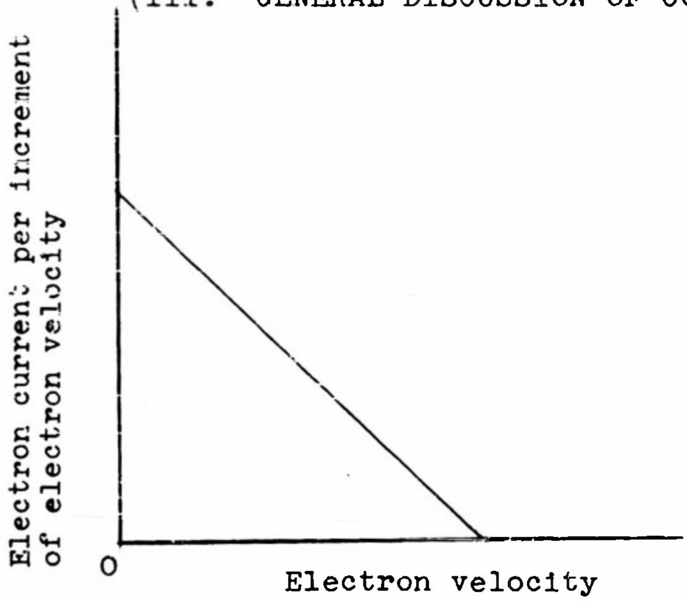


FIG. 3.2--Electron current per increment of electron velocity vs electron velocity.

three-electrode collector can recapture 49 per cent. This corresponds to net tube efficiencies of 46 per cent and 65 per cent for a klystron whose r-f efficiency is 33 per cent.

It was with the goal of 65 per cent in mind that work was initiated on a three-electrode collector.

In the design of a collector, a number of precautions should be observed. Any device which will reflect electrons back into the r-f section must be ruled out. The necessity of this is two-fold. Electrons delivered at random to the output gap would generally reduce the power delivered to the circuit. More serious is the influence of stray electrons entering the input gap where the r-f power level of a typical three-cavity tube is lower by a factor of several thousand. If only electric fields are present, any electron which is brought to a standstill before reaching a collector electrode will be reflected back along its original path.

## IV. COLLECTING AND VELOCITY-SORTING DEVICES

Two important functions must be performed in the collector. The high-velocity electrons must be sorted from the low-velocity electrons in such a manner that they will go to the proper electrode. Obviously, a high-velocity electron that strikes a low-voltage electrode does not give up as much energy as it would if it reached a high-voltage electrode. Second, the electrodes must be capable of capturing and holding the electrons which should properly go to it.

### A. VELOCITY SORTING

A number of velocity-sorting devices immediately come to mind. A transverse magnetic field or electrostatic deflection plates similar to those used on cathode-ray tubes will deflect low-velocity electrons more than high-velocity ones. It is possible to think of many axisymmetric electrostatic deflection schemes which will cause the electrons to "fountain" outward.

All these devices run into one difficulty. The space-charge forces of the high-perveance beams typically used in klystrons have a greater effect on the electron paths than do any external forces.

The obvious answer to this difficulty is to use the space-charge forces to velocity-sort the beam.

A beam of mixed velocities even in a region free from all forces except space-charge forces will sort itself in such a manner that the slow electrons will be on the outside of the beam and the core will be composed of fast electrons. The sorting is not perfect since even slow electrons right on the axis are subjected to no radial force, but one would expect the over-all sorting to be reasonably good.

B. COLLECTING

The problem of collector design resolves itself into one of selecting a suitable arrangement of electrodes. To be compatible with the space-charge sorting, the collector device should obviously be axisymmetric.

A variety of collector electrode shapes are sketched in Fig. 4.1. All of them take advantage of the space-charge velocity sorting which causes the electrons to move to the outside of the beam.

Fig. 4.1(a) is included to indicate one difficulty that can be encountered. There is a similarity between the electrons entering the retarding field of the collector and a ball thrown into the air in the gravitational field. The ball must be thrown vertically to reach the highest distance. Likewise, the electron must move in the direction of the electric field lines in order to move to the highest potential possible. In Fig. 4.1(a) the electrons are always acted on by a radial force outward, so that electrons which have sufficient kinetic energy to reach the collector actually slide off to the side and fall back to ground (the body of the tube).

The collector shown in Fig. 4.1(c) seemed to offer the greatest possibility of success. Slow electrons entering the lower chamber are most likely to hit the top surface

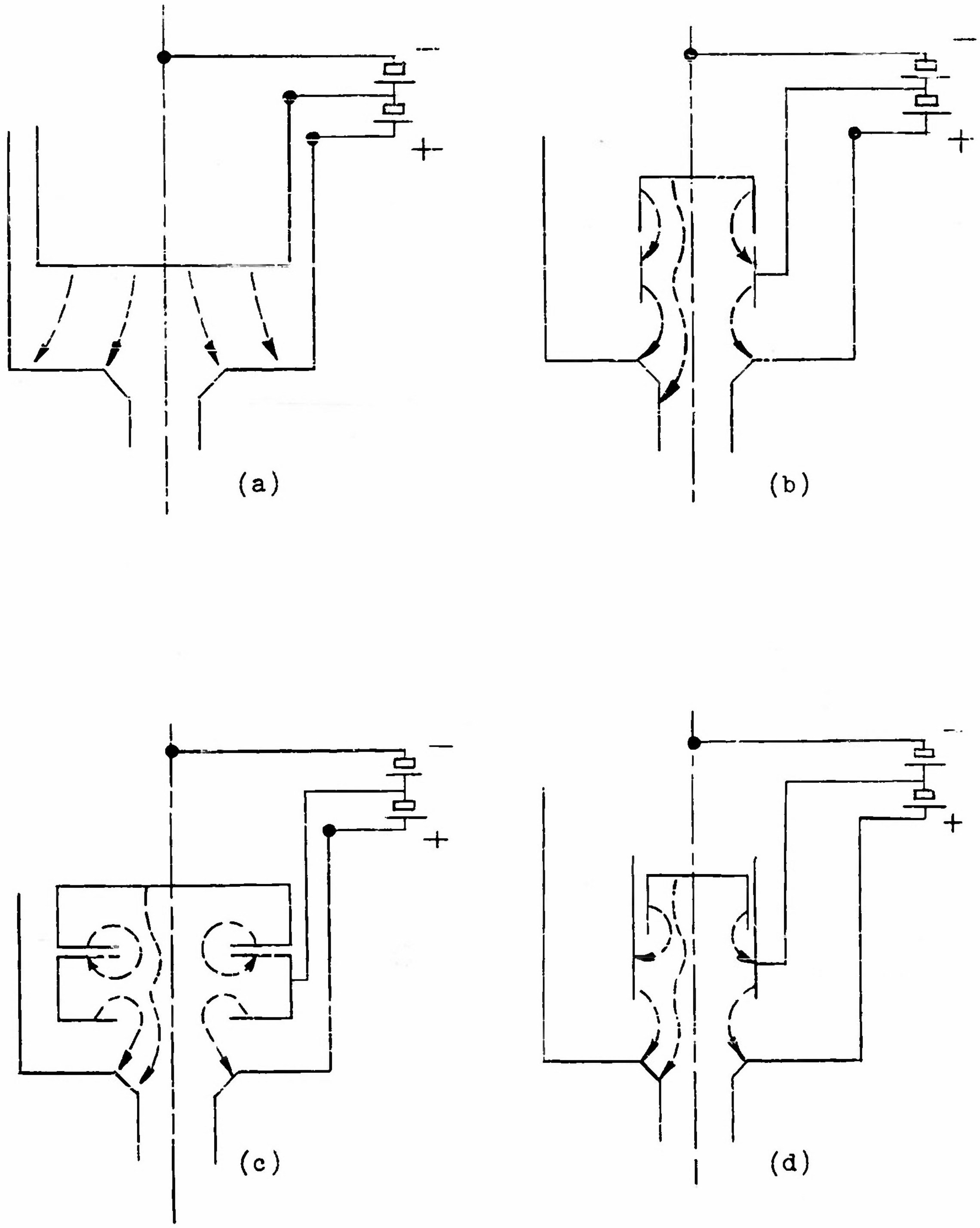


FIG. 4.1--Collector electrode shapes
(force on electrons indicated by dotted lines).

where the field is such as to reflect the secondary electrons back into the surface. This feature is inherent in all chambers except that at the highest voltage. The fast electrons presumably go straight through into the end chamber.

The radial field oscillates so as to accelerate electrons first outward and then inward. The longitudinal field along the axis is essentially constant. The fields within the chambers are relatively low. For the most part, the electric flux lines from the lower half of any chamber are directed to the upper half of the next chamber below. This should reduce the possibility of electrons returning to the drift tube.

The large sizes of the chambers adapt themselves to cooling.

Unfortunately, the space-charge forces are so large as to eliminate the possibility of determining electron trajectories from a Laplace solution of the fields in the collector region, so that any collector design will rely on educated guesses.

## V. DESCRIPTION OF COLLECTOR

### A. KLYSTRON

A part of the project was the design and construction of a high-power pulse klystron. The klystron parameters were chosen in such a fashion that the tube would be useful for such applications as driving linear electron accelerators. The outgrowth of this design are the Type 272 klystrons built at Stanford University. The original design had anticipated 2 Mw r-f output, 40 per cent efficiency, cathode perveance $2.0 \times 10^{-6}$ amp/$v^{3/2}$, 25 kw of average beam power, and 10 μsec pulse length.

The design was such that either two- or three-cavity tubes could be built, the simple addition of one cavity and a drift tube being the only difference. An assembly drawing of the three-cavity tube is shown in Fig. 5.1.

Since electrons reflected from the collector to the input cavity might cause some difficulties, the special collector design was made on a two-cavity version.

The klystron was tested without any special collector to ascertain the operating performance of the tube.

The efficiency was lower than anticipated, being only 30 per cent at 2 Mw. A survey of test data and design calculations indicated that the beam diameter was possibly too small.

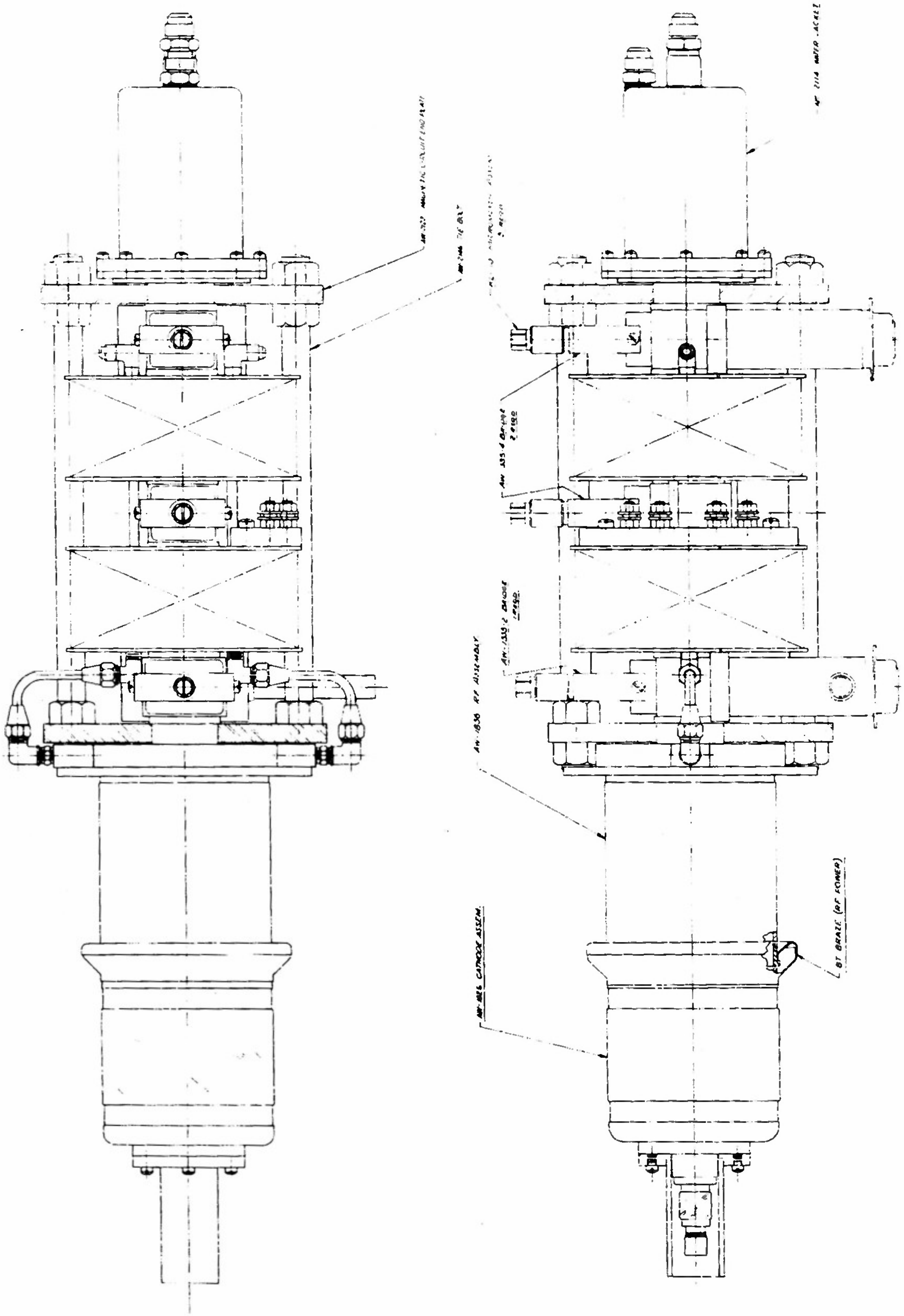

FIG. 5.1--Klystron assembly drawing.

The pertinent data for the collector design are that the output gap spacing is 1.0 radians (0.355 in.) at 90 kv, the drift tube radius is 1.1 radians (0.781 in.), and the peak output gap voltage is equal to the d-c beam voltage.

B. COLLECTOR

In the previous section it was indicated that a collecting device composed of a series of chambers offered some promise of success. It was this sort of device that was assembled and tested. Since the beam spreads so rapidly following the output gap, the collector was designed in such a manner that a longitudinal magnetic field could be applied to constrain the beam and also to reduce the possibility of returning electrons.

The velocity-sorting action is due mostly to the space-charge forces. The electrons are caught in the chambers if they move far enough radially.

The geometry of the chambers was chosen to reduce the possibility of electrons returning to the drift tube. The holes in the chambers were four times the area of the drift tube. The length of the chambers was chosen such as to give an opportunity for the velocity-sorting action to take place and to give the electrons time to move radially into the chambers.

An equipotential plot for the fields in the chambers is shown in Fig. 5.2. Because of the shape of the chambers, there are radial fields in addition to the longitudinal fields. The maximum radial field is about one-half the maximum longitudinal field which was of the order of 30 kv/in.

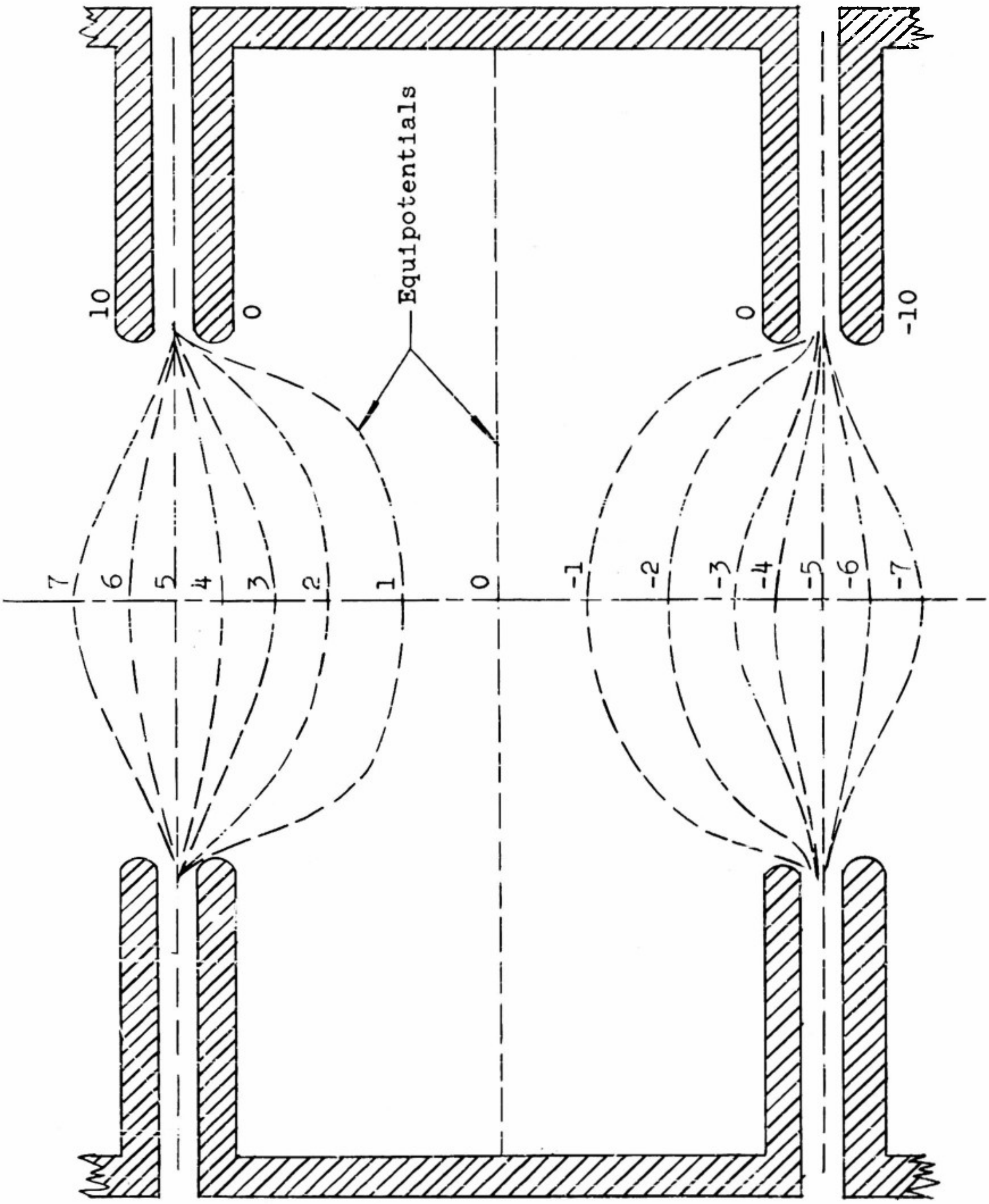


FIG. 5.2--Equipotential plot of collector chamber (4 x scale).

The chamber fields are of the same order of magnitude as the space charge fields. The radial field of a 1-in. diameter, 80-kv, perveance $2.0 \times 10^{-6}$ amp/$v^{3/2}$ beam is 11.4 kv/in. at the beam edge.

In the retarding field region the beam will spread faster than in a region free of external fields. However, some idea of the spreading can be gained by studying the field-free spreading curves, a few of which are shown in Fig. 2.3.

An estimate of a suitable collector design was made which took into account the fact that the magnetic field would constrain the beam somewhat, and the necessity for utilizing existing materials as much as possible. An assembly drawing of the collector is shown in Fig. 5.3.

The klystron is mounted with its cathode end down in a tank of oil. The collector magnet coil form doubled as a second tank of oil to protect the collector ceramic seals which insulated the collector chambers from one another.

A single loop of Tygon plastic tubing between each chamber provided it with cooling water. The collector was capable of dissipating some 10 kw of average power.

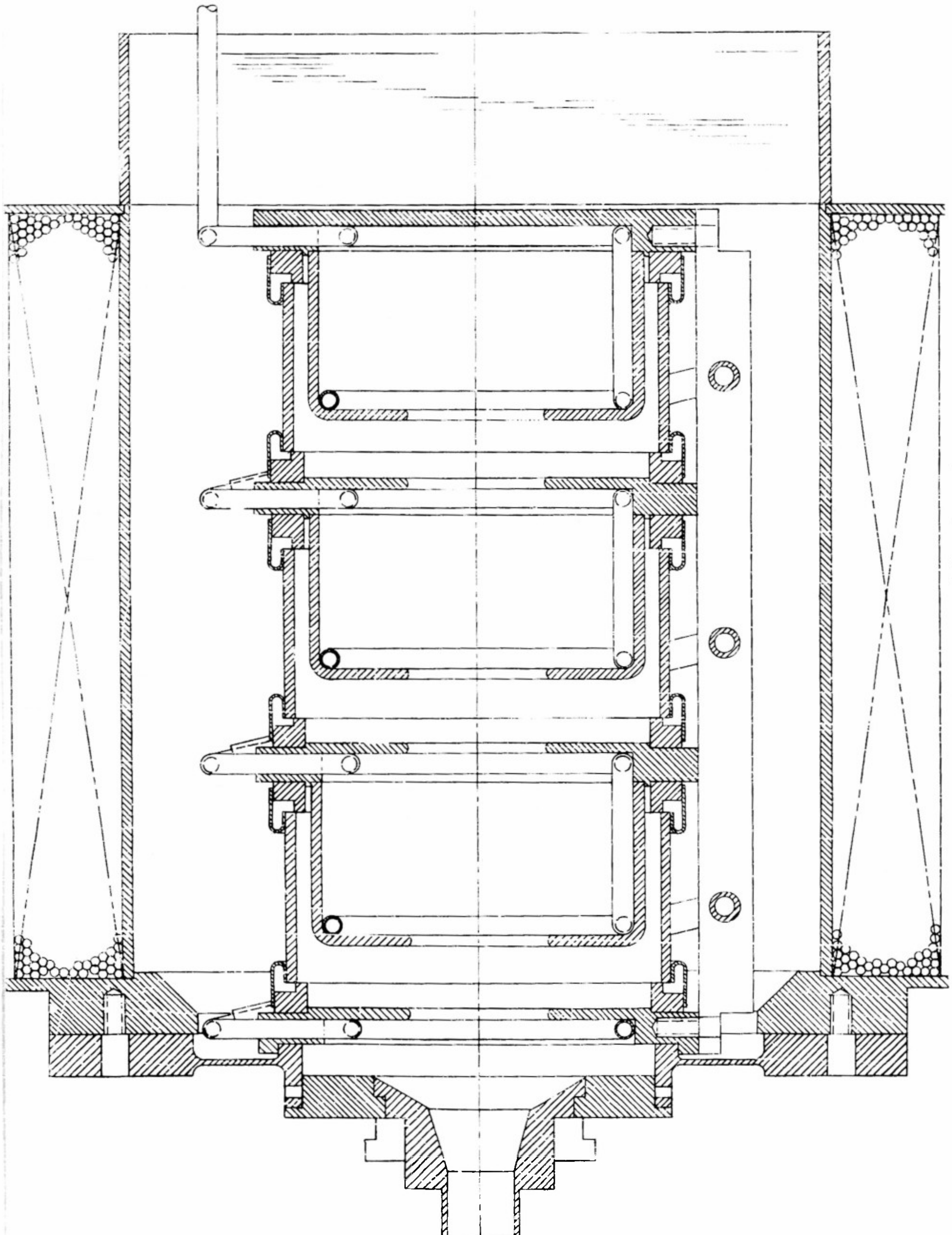

FIG. 5.3--Collector assembly drawing.

## VI. EXPERIMENTAL DATA

A 2-Mw klystron was disassembled and rebuilt including the special collector described in the previous section. Due to failure of a glass vacuum window during processing of the tube, the cathode became temperature limited at voltages greater than 30 kv. This upset the beam focusing so that without r-f drive, the maximum beam transmission was 86 per cent. The gain and efficiency are low enough that some fraction, say, 15 per cent, of the beam might be assumed to be lost before the beam reaches the output gap. Since one might presume the beam is off center, the collector operation should not be as good as is possible.

Previous data indicated the tube operated properly into a matched load. With the temperature-limited cathode, the tube output is a maximum with a load resistance 1.9 times a matched load.

### A. MEASURING TECHNIQUE

The object of the tests is to measure the increase in tube efficiency achieved by the collector. The r-f output, d-c beam input, and collector-chamber average powers are sufficient data for a calculation of the efficiencies. This avoids the measurement of pulse length. The average power is, of course, the product of voltage and average current.

The r-f power output was measured with a thermistor operated in a d-c bridge circuit.

The pulser circuit is shown in Fig. 6.1. Three separate devices gave a check on the beam voltage: (1) the voltage rise on the 32-$\mu$f condenser; (2) the peak reading voltmeter; and (3) the condenser voltage divider. The collector voltage can be calculated from the transformer turns ratio and checked with the condenser voltage divider.

The average currents into the collector and body of the tube are known. However, if the tube is not matched to the pulse line, this measured current may be greater than the average current due to the initial pulse, because the pulse line retains some charge after the initial pulse. If the tube impedance is 50 per cent more than a matched impedance, the average current reading will be 25 per cent too high. This mismatch is indicated by a stepped beam-pulse shape in which the second step is 20 per cent of the initial pulse amplitude.

The result of feeding power from the collector to the pulse transformer does not lower the required pulser supply voltage, but rather increases the effective tube impedance. In any event, on a line type pulser, the beam voltage is a function of the r-f operation of the tube.

The r-f drive pulse width was made longer than the klystron beam pulse so that the tube would be operating under substantially the same conditions throughout the pulse.

## B. EXPERIMENTAL RESULTS

Figs. 6.2 through 6.4 show the klystron operation with all the collector electrodes grounded. The low efficiency of the existing tube compared to the previous data indicates the difficulty encountered with the beam focusing.

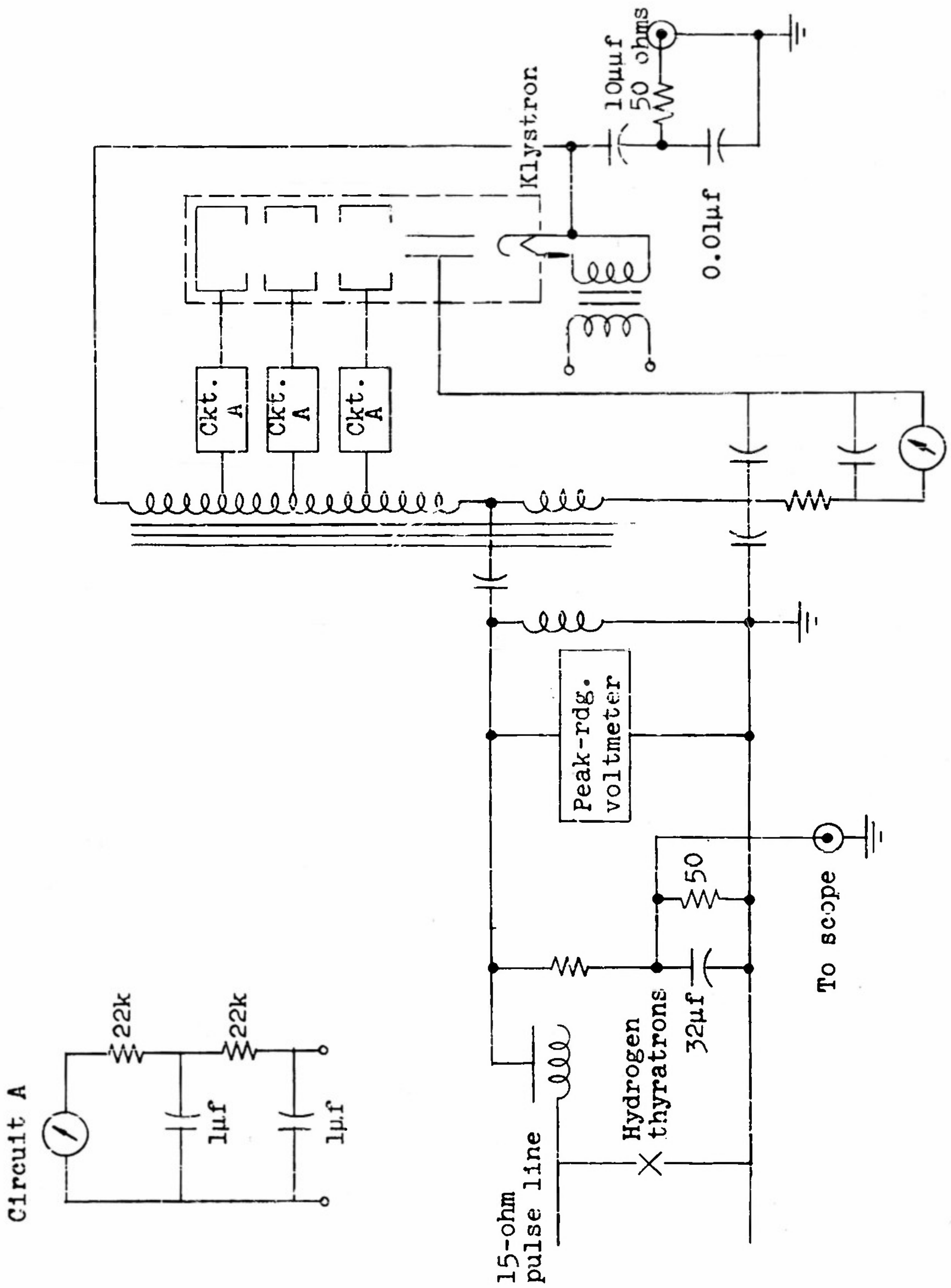


FIG. 6.1--Circuit Diagram.

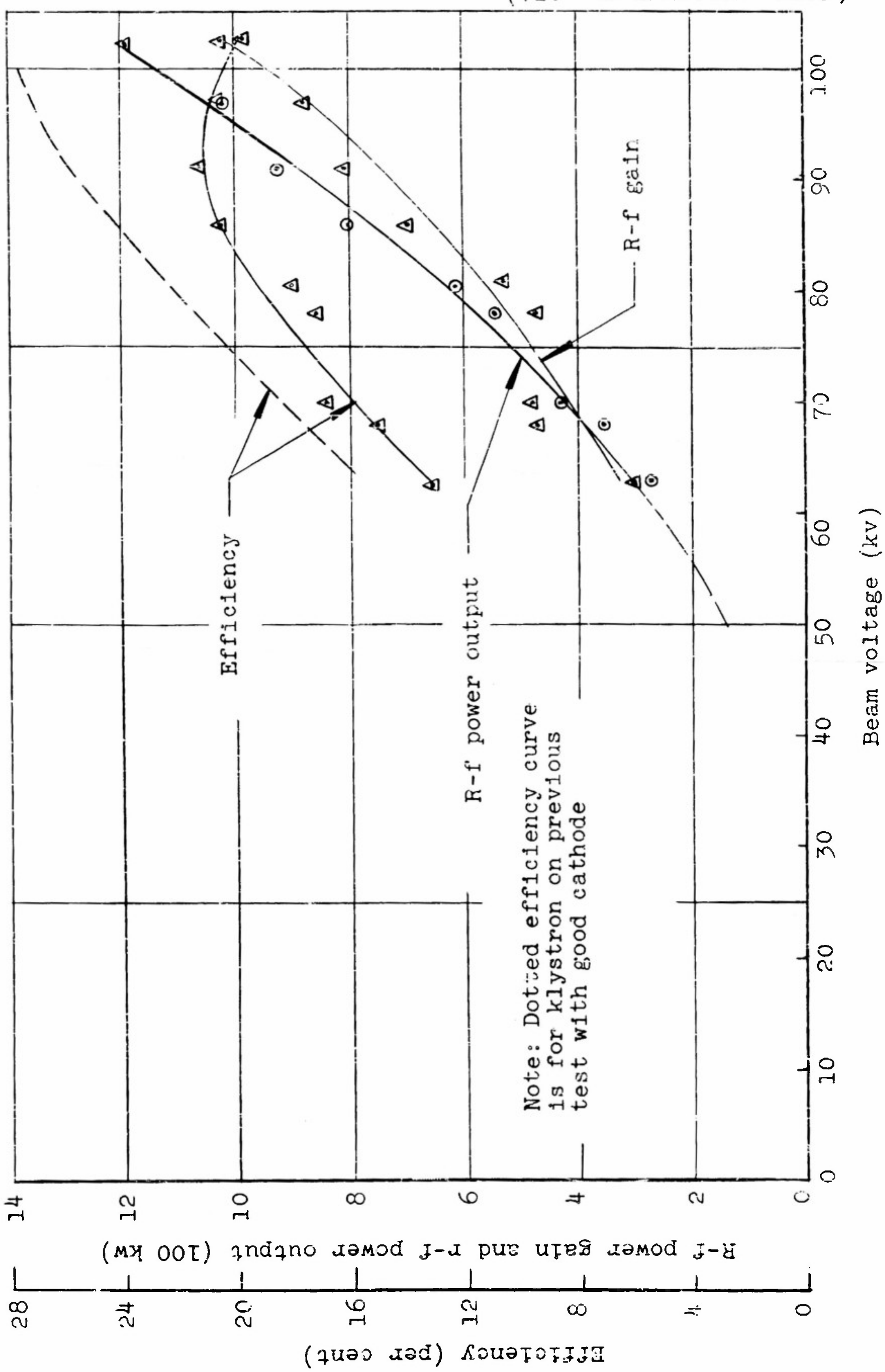


FIG. 6.2--R-f power output, r-f power gain, and efficiency vs beam voltage.

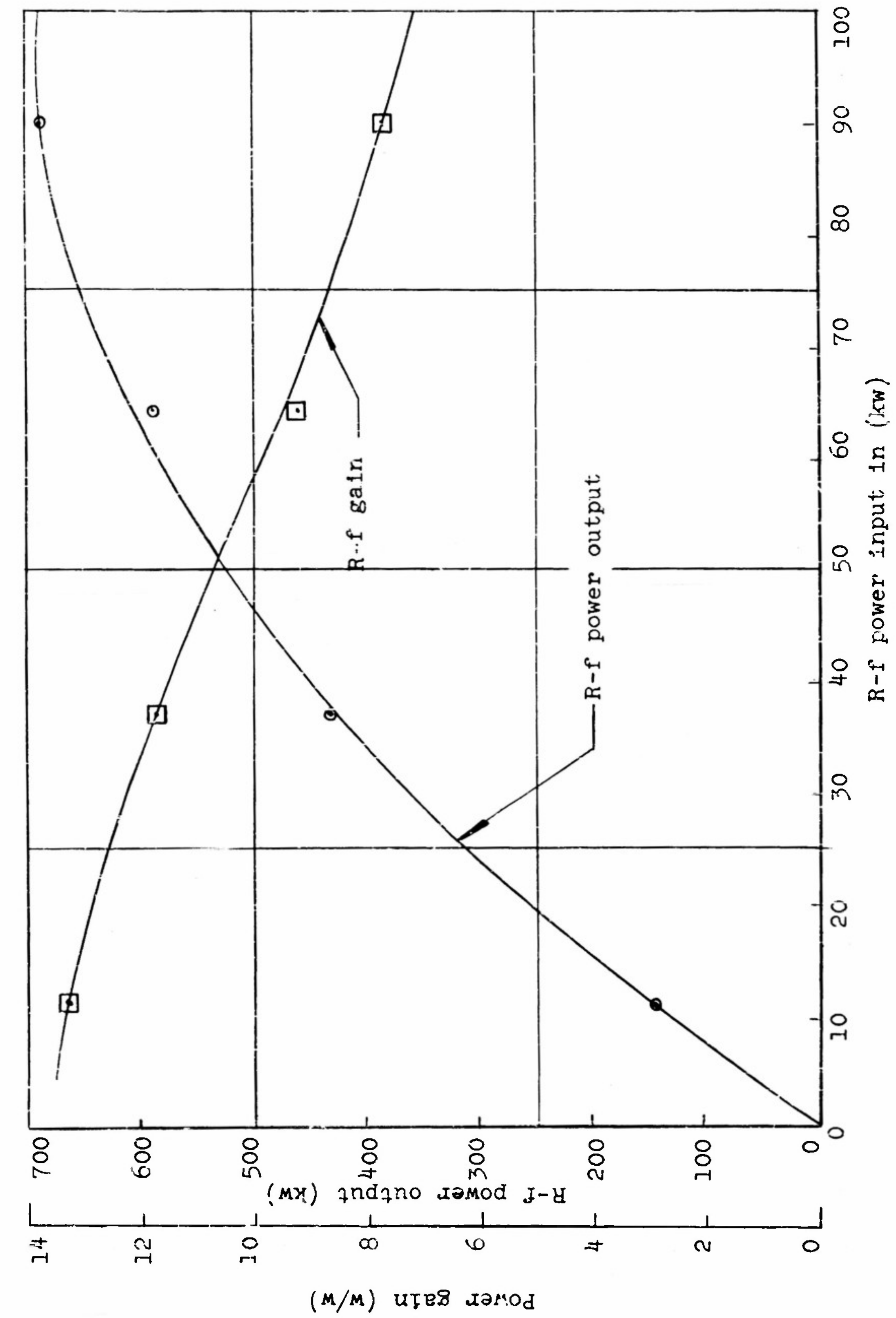


FIG. 6.3--R-f power output and r-f power gain vs r-f power input.

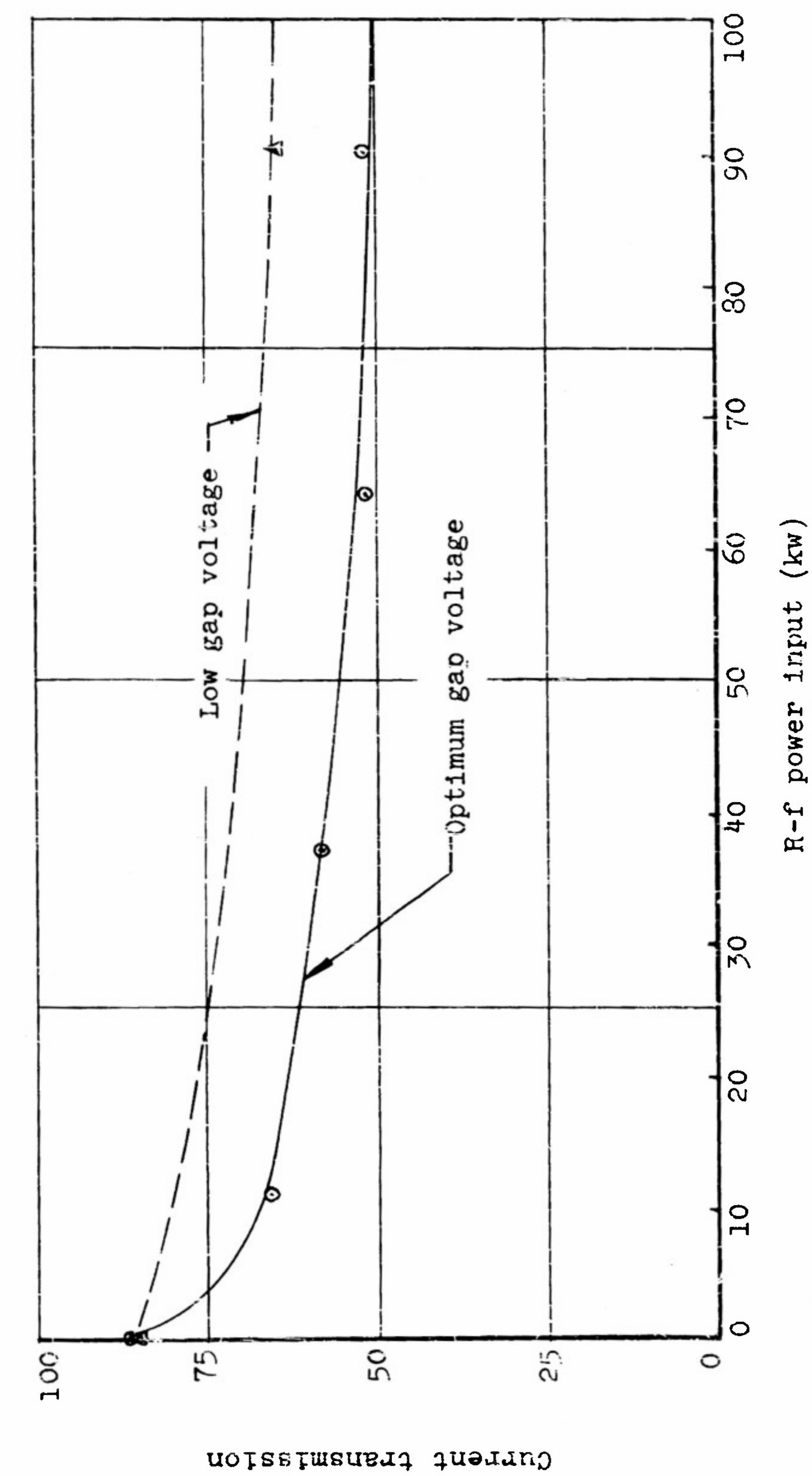


FIG. 6.4--Current transmission vs r-f power input.

The collector efficiency curves are taken at 80-kv beam voltage which corresponds to 42.1 amp and a perveance of $1.86 \times 10^{-6}$ amp/$v^{3/2}$. The Figs. 6.5-6.7 are taken with the three chambers at the same potential, a one-electrode collector.

The longitudinal magnetic field did not improve the collecting efficiency in any but the case shown in Fig. 6.10. Hence the field is zero for all except as noted there.

A symptom of trouble is noted in the curve for no r-f, Fig. 6.5. The beam transmission is 65 to 85 per cent. The loss of 15 per cent of the beam with a grounded collector is a result of the poor focusing. Another 20-percent loss at high collector voltages indicates that either electrons are not reaching the chambers or that secondary electrons are falling back from the chambers to the tube body.

The high output gap voltage curve corresponds to the klystron output cavity loaded for optimum power output. The low output gap curve is for a matched load in the output waveguide.

The product of current transmission in per cent of beam current and collector voltage in per cent of beam voltage is the power captured by the collector in per cent of beam power. This we define as collector efficiency.

Figs. 6.6 and 6.7 are derived from Fig. 6.5. Fig. 6.6 should be compared with Fig. 3.1 to ascertain whether this collecting device is capturing as much power as is available in the beam. The r-f efficiency of the klystron at this voltage is only 19 per cent, while the theoretical data were for

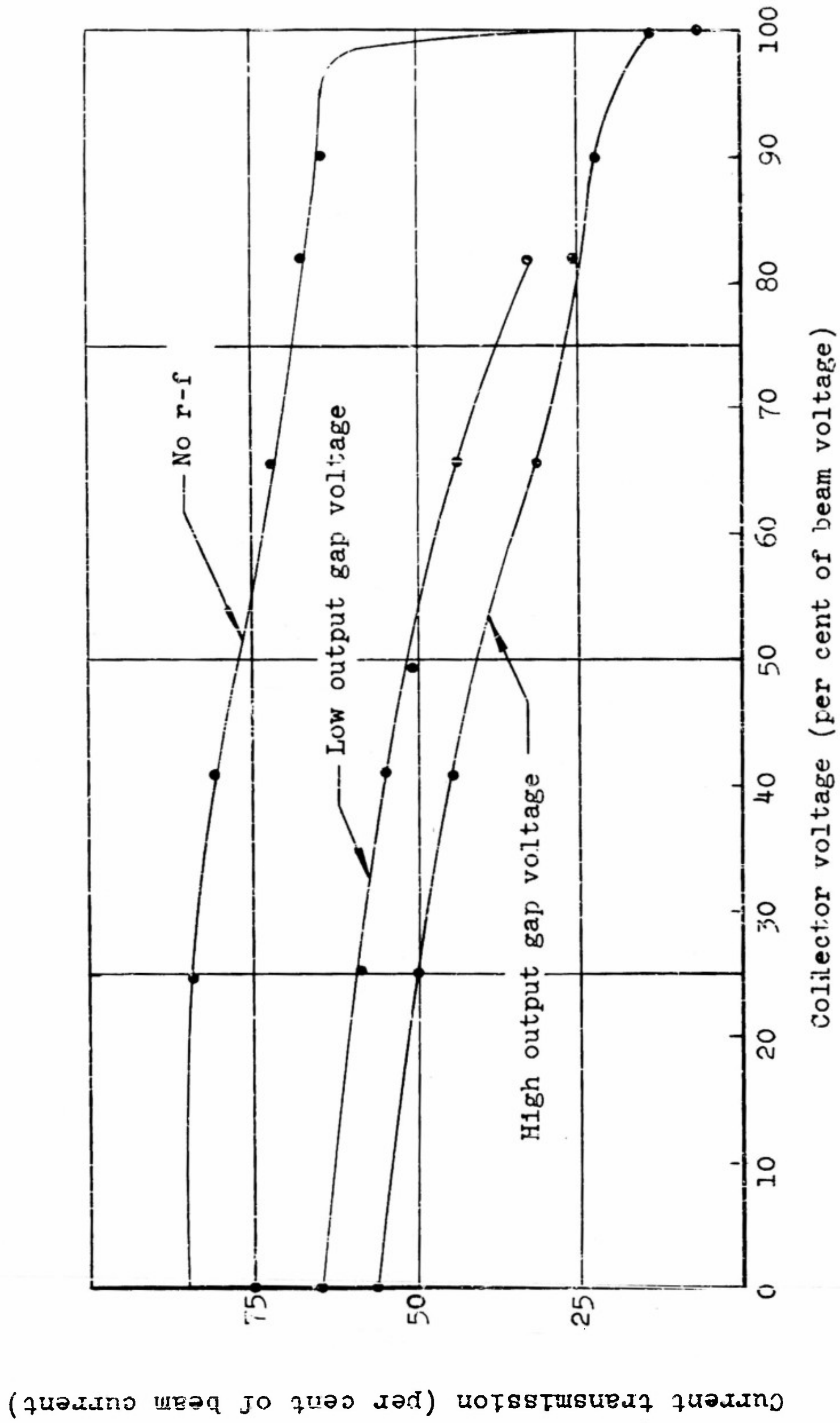


FIG. 6.5--Current transmission vs collector voltage.

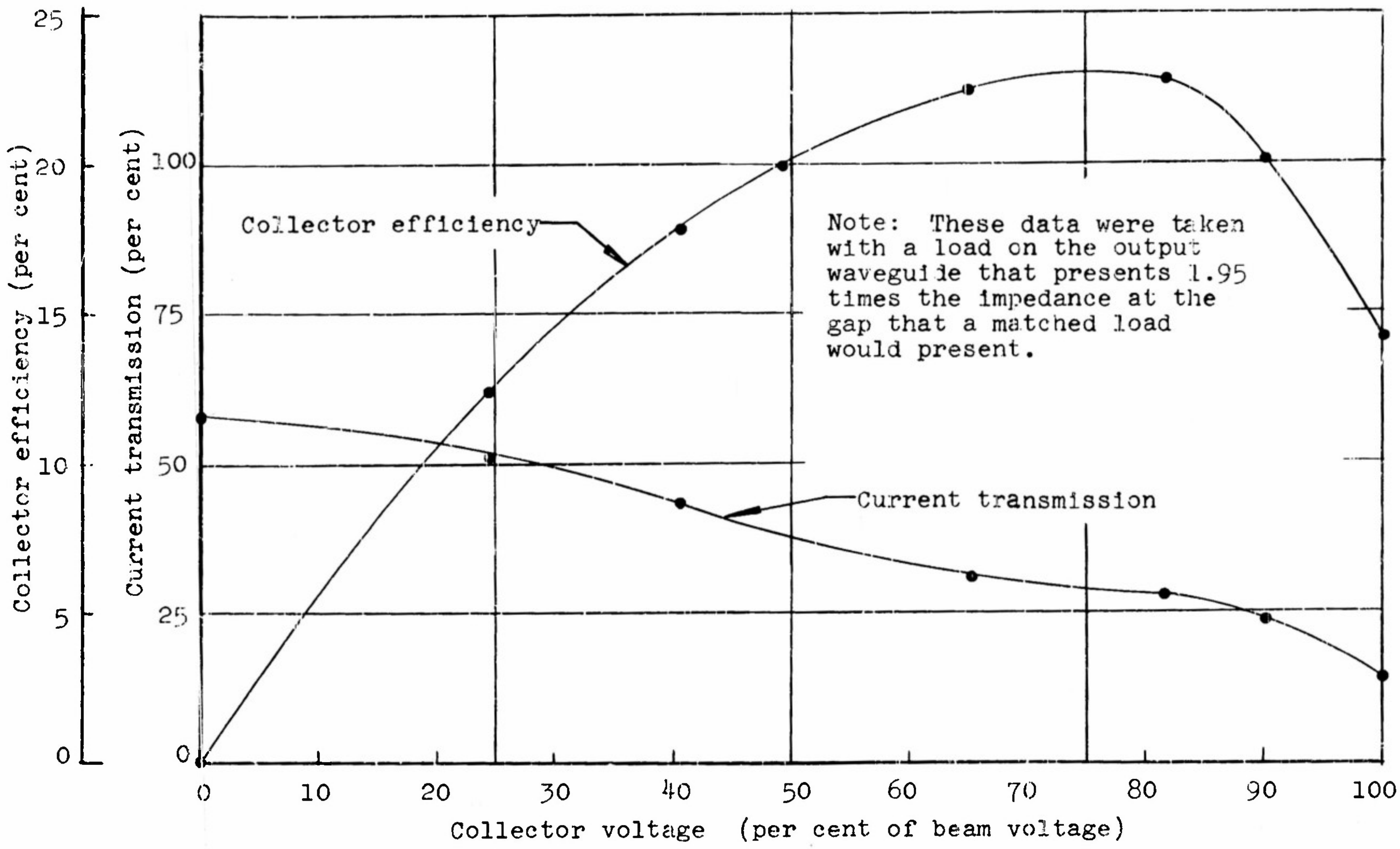


FIG. 6.6--Collector efficiency and current transmission vs collector voltage.

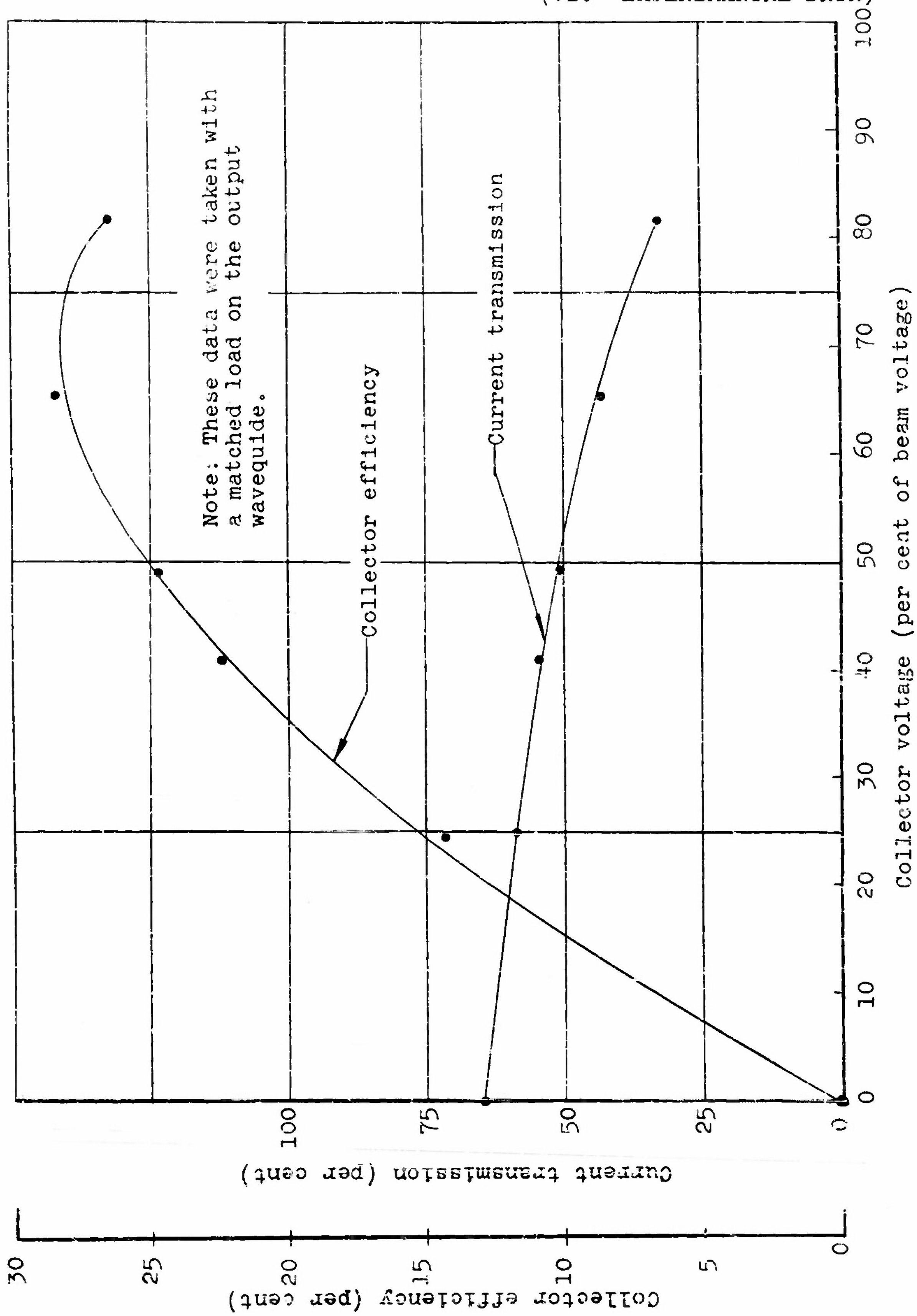


FIG. 6.7--Collector efficiency and current transmission vs collector voltage.

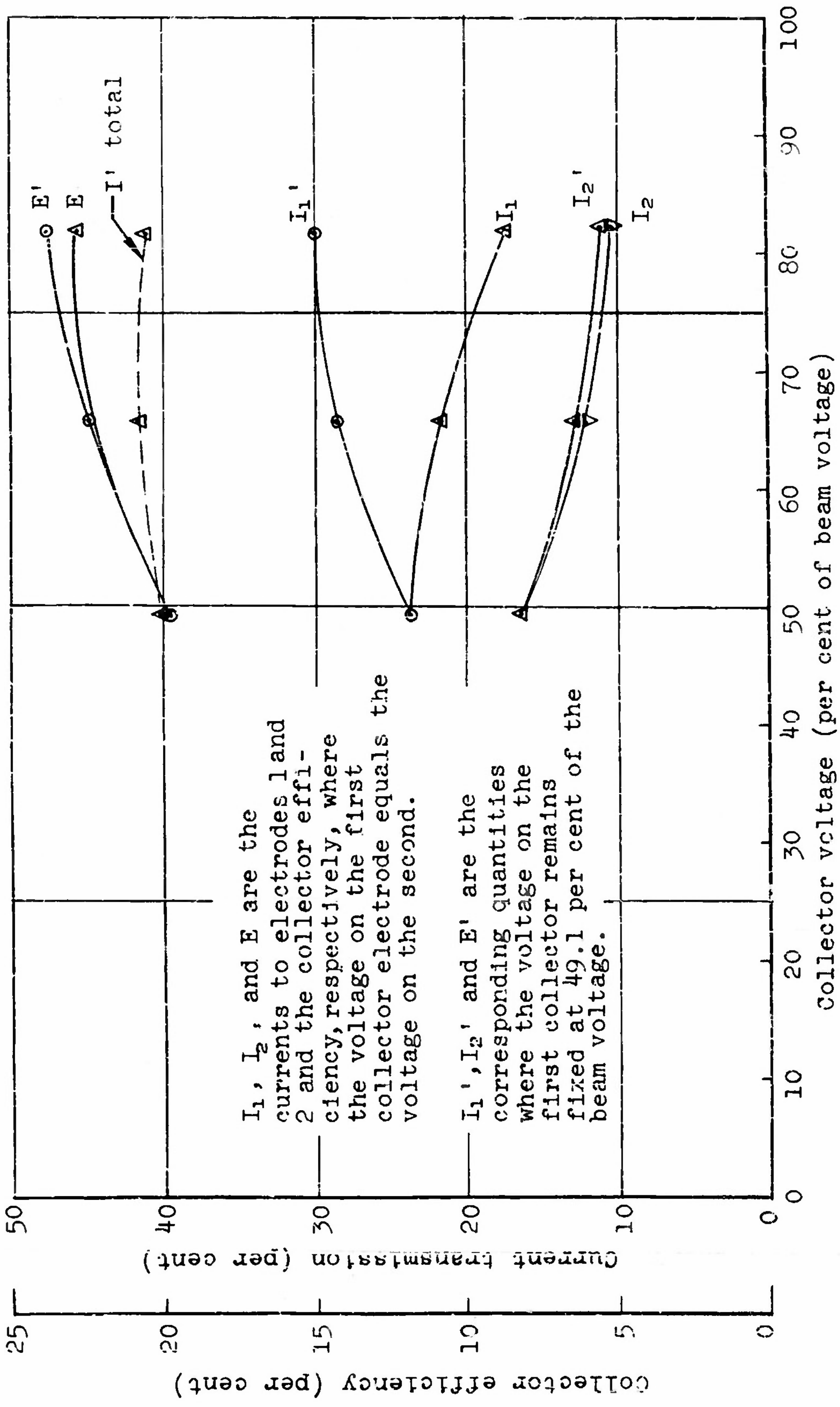


FIG. 6.8--Collector efficiency and current transmission vs voltage on first electrode of a two-electrode collector.

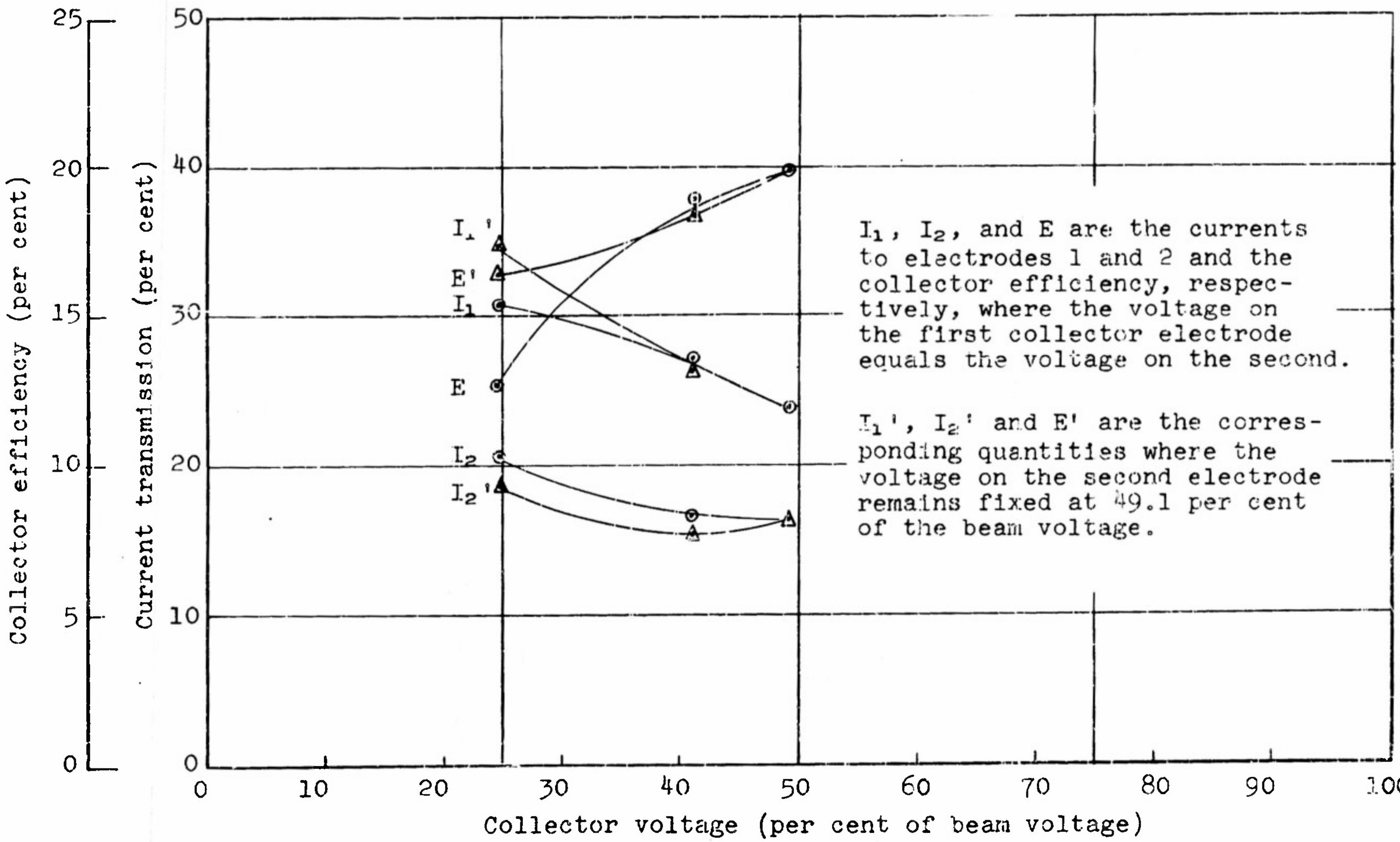


FIG. 6.9.--Collector efficiency and current transmission vs voltage on first electrode of a two-electrode collector.

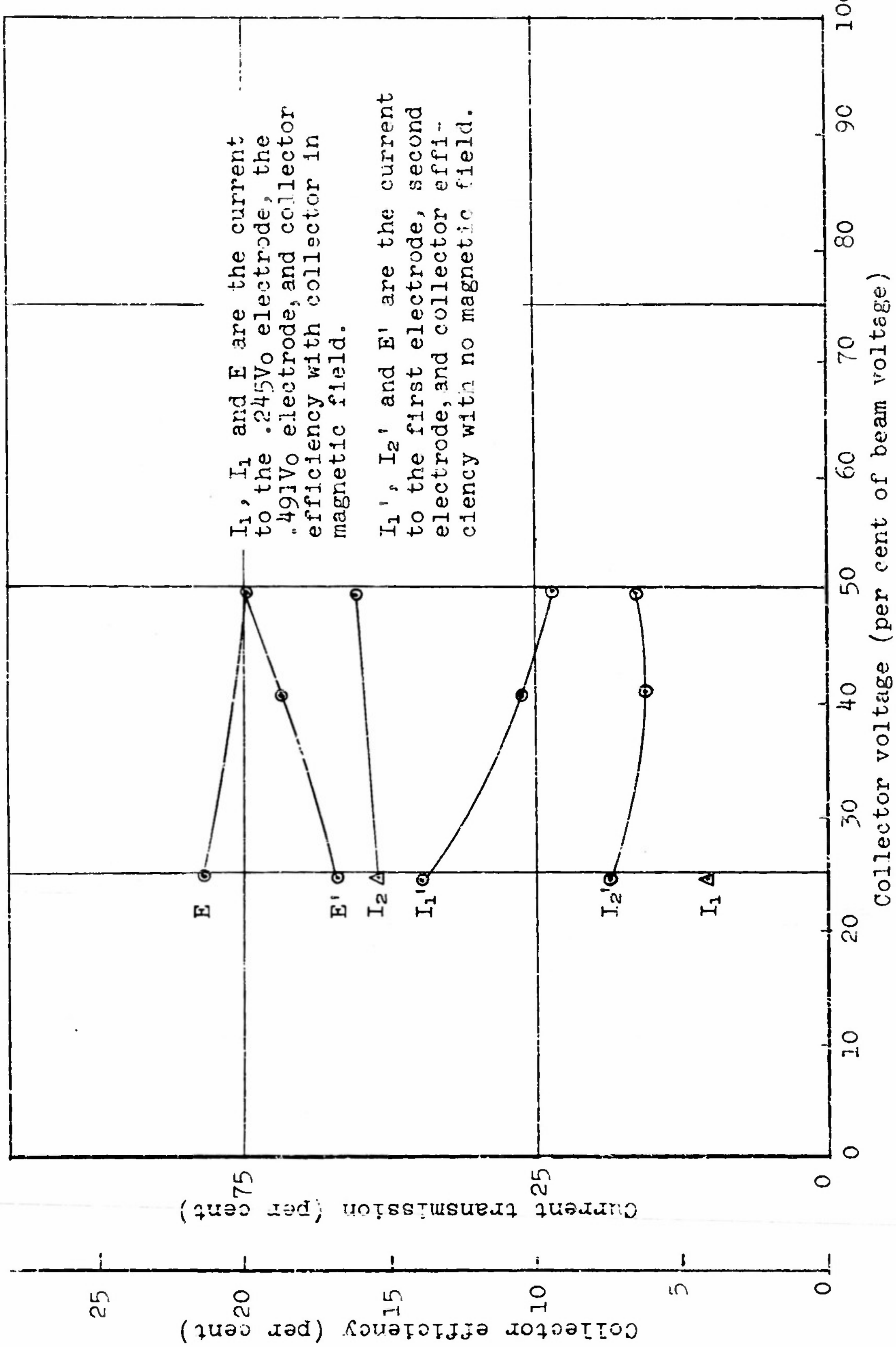


FIG. 6.10--Collector efficiency and current transmission vs voltage on first electrode of a two-electrode collector.

an r-f efficiency of 33 per cent. The measured peak collector efficiency is 23 per cent. The theoretical efficiency is 29 per cent. There is a wide divergence from theory in the shape of the curve, the theoretical curve being much higher on the low voltage end. The space-charge forces may cause an interchange of energy between electrons but perhaps a better explanation is that the low-voltage electrons are spreading so fast following the output gap that they never reach even the first collector chamber.

Figs. 6.8 through 6.10 indicate the gain in efficiency obtained by using a two-electrode collector rather than a single-electrode collector. The gain in efficiency was disappointingly small: the highest efficiency was 24 per cent, a gain of 1 per cent over a single-electrode collector. The change in efficiency for a triple-electrode collector was undetectable. The theory had indicated collector efficiencies of 49 per cent for a perfect triple-electrode collector.

Two things might account for this: one is the beam spreading of the low-velocity electrons, and the other is the collector may be too long so that even the high voltage electrons are spread too much. The magnetic field which had been counted on for such an eventuality may cause the electron beam to converge too much at just the wrong time so that the electrons fall back through the holes in the chambers and are lost.

Secondary electrons which had been a matter of great concern may be no problem at voltages in the vicinity of 80 kv.

Data available[1] indicate a falling off of secondaries at high incident voltages. If they had been a problem in this design, the two-electrode collector should work considerably better than the single-electrode type.

---

[1]K. R. Spangenberg, Vacuum Tubes, McGraw-Hill Book Co., New York, 1948.

## VII. POSSIBLE IMPROVEMENTS

It is quite likely that it will be impossible in any simple design ever to extract the energy of the low-velocity electrons due to their rapid spreading following the output gap.

If one were satisfied with a single-electrode collector, it seems likely that 30 per cent of the beam power could be extracted. The most obvious step to improve the design would be to reduce the spacing between the chamber and the output gap. Four possible single-electrode collectors are shown in Fig. 7.1. Figs. 7.1(c) and 7.1(d) assume the glass or ceramic path is long enough to withstand the pulse voltage in air.

Provision must be made in all cases to cool the collecting chamber, to provide a high-voltage lead, and to she shield the collector with lead.

A typical ceramic cylinder 2 in. long has a pulse breakdown voltage of 270 kv in oil. A 1-in. seal should give a good margin of safety for 100-kv tubes.

It should be possible to make a 5- to 10-kw collector similar to Fig. 7.1(a), 5 in. in diameter and whose length from the output gap is only 6.5 in.

On a typical klystron whose r-f efficiency is 30 per cent, the addition of such a collector would raise the over-all efficiency to 43 per cent. Likewise a 40-percent efficient tube might be raised to 50 per cent.

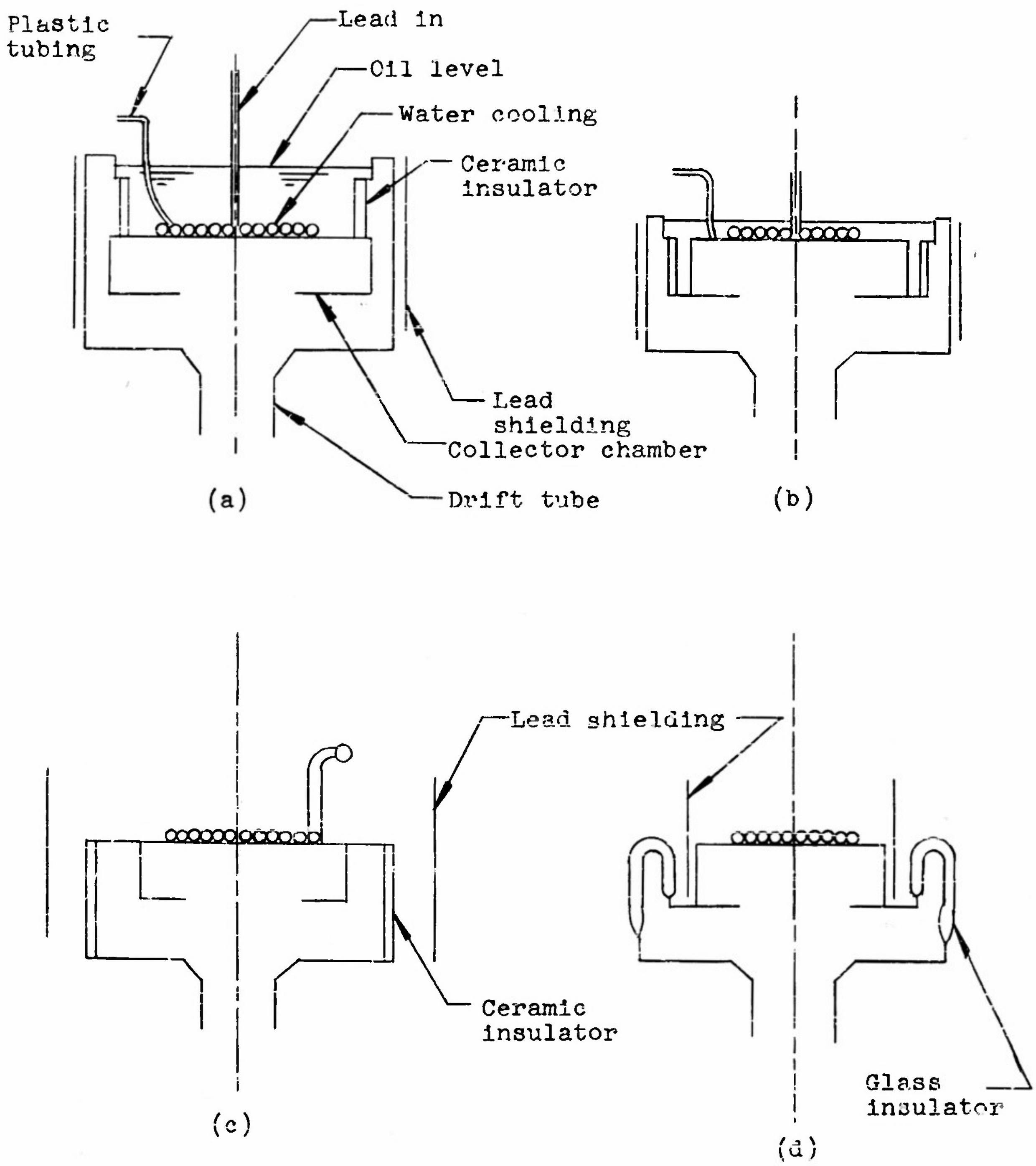


FIG. 7.1--Single-electrode collectors.

## VIII. CIRCUIT CONSIDERATIONS

A collector of the sort described when connected to a transformer, increases the effective impedance of the tube without decreasing the required voltage. This impedance of the tube is a function not only of the beam voltage but of the r-f power and the magnetic focusing. On a line-type pulser then, the beam voltage is in turn a function of the effective tube impedance. In a fixed operation, the pulse line would be matched to the effective tube impedance rather than the d-c beam impedance.

In general, without r-f drive, the collector efficiency is very high. It is possible for a perfect collector to cause a doubling of the beam voltage when the r-f drive is turned off. Care must be exercised to see that this will not damage the tube or that suitable interlocks are included in the circuitry.

## IX. CONCLUSIONS

A collecting device was designed, built, and tested which was capable of recapturing energy from the electron beam following the output gap of a klystron and feeding this energy into the pulse transformer such that the over-all efficiency of the klystron was increased. A single-electrode collector recaptured 23 per cent of the beam power. It was expected that a double- or triple-electrode collector would improve on this but the tests did not indicate any improvement. It is felt the difficulty is due to the extremely rapid spreading of a beam following the output gap.

The test did indicate that 30 per cent recovery of the beam power should be easily realized by a single-electrode collector. The optimum collector voltage (about 75 per cent of beam voltage) is simply tapped from the pulse transformer with pulse tubes. 30 per cent recovery implies a 30-percent reduction in power supply current, with obvious savings in component costs and electric power costs over the life of the tube. In high-power tubes it would indeed seem practical to add such a collector.

APPENDIX

The following indicates a construction for finding the exit velocity and time of an electron in a gridded gap.

An electron injected into a region between two parallel planes is subject to the acceleration

$$a = \frac{F}{m} = \frac{-Ee}{m} = \frac{eV}{md} \sin \omega t = \frac{\omega u_0 \alpha}{2D} \sin \omega t$$

if the voltage between the plates is V sin $\omega t$.

Integration of the acceleration gives the velocity

$$u = u_0 \left[1 + \frac{\alpha}{2D} (\cos \omega t_1 - \cos \omega t)\right]$$

and a second integration gives the position of the particle,

$$Z = \frac{\alpha}{2D} (\sin \omega t_1 - \sin \omega t) + \left(1 + \frac{\alpha}{2D} \cos \omega t_1\right)(\omega t - \omega t_1)$$

These equations satisfy the boundary conditions that $Z = 0$ and $u = u_0$ at $\omega t = \omega t_1$.

If $\frac{1}{\alpha/2D}\left(Z + \frac{\alpha}{2D} \sin \omega t\right)$ is replaced by Y, then

$$Y = \sin \omega t_1 + \left(\frac{1}{\alpha/2D} + \cos \omega t_1\right)(\omega t - \omega t_1)$$

A plot of Y vs $\omega t$ is recognized as a straight line of slope $\left(\frac{1}{\alpha/2D} + \cos \omega t_1\right)$ passing through the point $Y = \sin \omega t_1$ when $\omega t = \omega t_1$.

It is noted that $\cos \omega t_1$ is the slope of $\sin \omega t_1$. The construction line indicated in Fig. A.1 is drawn as an

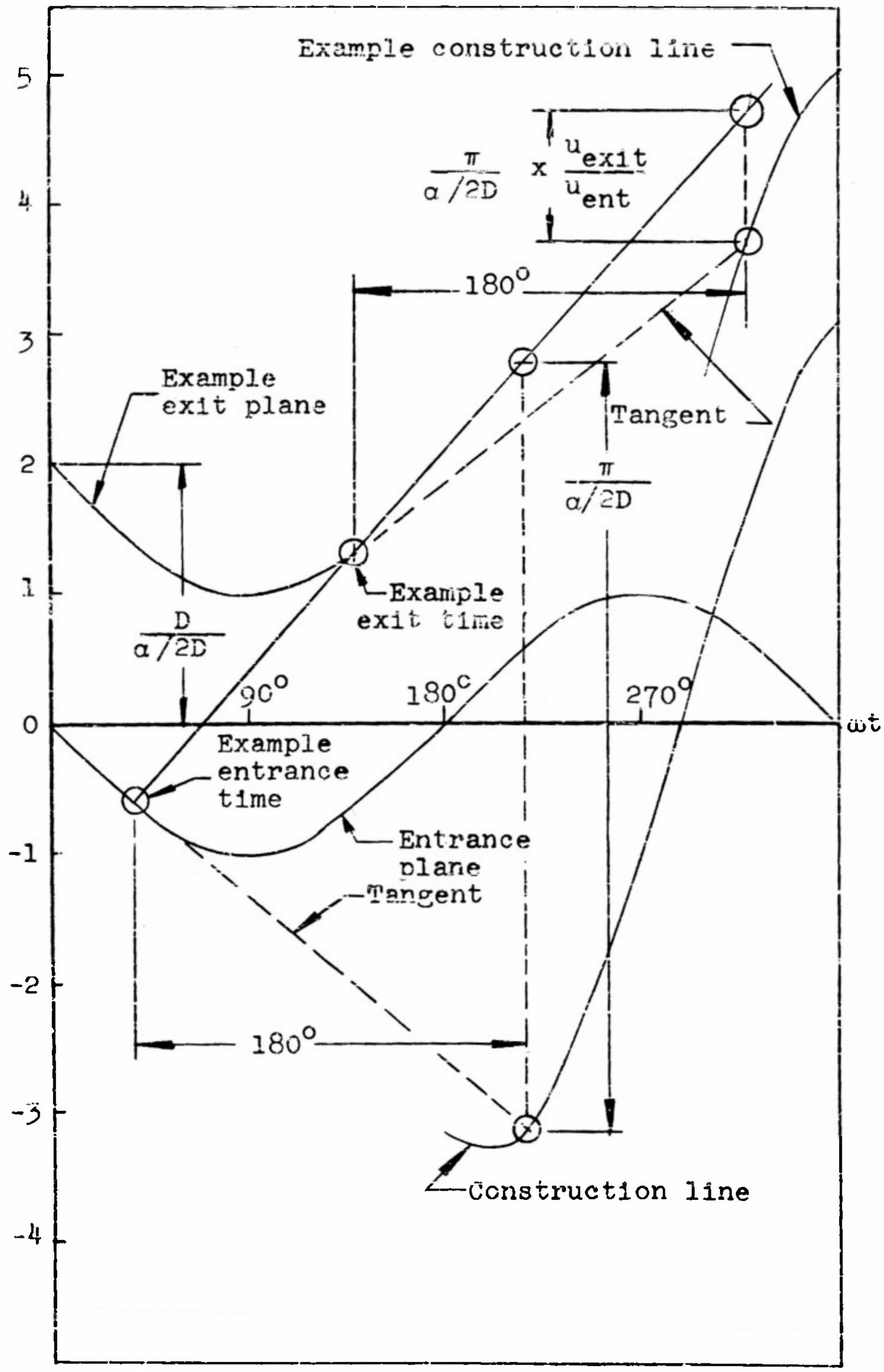


FIG. A-1--Construction for determining electron exit potential and time of exit for electrons passing through gridded gaps.

aid to finding the slope of sin $\omega t_1$. Rather than measuring the slope over an increment of 1 radian, the construction line is drawn in such a manner that the slope is measured over $\pi$ radians ( $= 180^\circ$). The ordinal distance is therefore $\frac{\pi}{\alpha/2D}$ rather than $\frac{1}{\alpha/2D}$ .

The distance between the entrance and exit planes in terms of Y is $\left(\frac{1}{\alpha/2D}\right)D$.

It is useful to copy the exit plane and its construction line on tracing paper and lay it over Fig. A.1 so as easily to adjust the gap spacing, $\frac{D}{\alpha/2D}$ .

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